FINITE ELEMENT MODELING OF TRANSDUCERS FOR UNDERSEA ULTRASONIC IMAGING

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ABSTRACT

Under ONR contract N00014-94-C-0047 Weidlinger Associates participated in a TTCP collaboration among United States, United Kingdom, and Canadian researchers on design and construction of a composite transducer array for undersea ultrasonic imaging. Our primary objective was to collaborate on finite element modeling techniques with Prof. Gordon Hayward's Ultrasonics Research Group at the University of Strathclyde. Specifically, we provided multiple licenses of our time-domain finite element code, PZFlex, trained one of their graduate students at our office, developed enhanced analysis capabilities within the code framework, and helped apply the modeling code for a better understanding of transducers and transducer materials used in undersea ultrasonic imaging systems. In addition, to support the overall TTCP collaboration, we supplied limited numerical modeling for the other groups involved, specifically, Fugro-UDI, Ltd., Material Systems, Inc., Ultrasound Solutions, and the Royal Military College of Canada. These efforts are described herein, primarily through a technical paper and abstracts from briefings and meetings held three time per year (two TTCP group meetings and one ONR Review meeting).

BACKGROUND

High-resolution undersea imaging for mine detection and identification is recognized as an essential adjunct to modern naval operations. However, conventional, clear water, low frequency sonar technology does not offer a practical basis for such imaging because of the enhanced performance requirements and more complicated operating environment.

The problem is that mines are typically sitting on or in bottom sediments where the propagation and scattering is complicated and image resolution needed for identification is very fine compared to conventional sonar. In fact, the mine detection/identification problem bears a closer resemblance to medical ultrasound imaging. To accommodate these differences, conventional naval transducer designs, materials, wave forms, and signal processing must be reexamined, with strong emphasis on composite, broadband transducer technology.

Part of the solution is to utilize more complete mathematical/computer models of the transducer problem. These permit numerical simulation of critical phenomena so that designers can interpret experiments better, identify and quantify problematic issues, and validate solutions. In general, models allow the designer to augment

physical experiments with computer experiments—so-called virtual prototyping. A comprehensive modeling capability can reduce design cycle time significantly and result in more nearly optimum solutions. However, until recently the necessary modeling software was unavailable. Basic capabilities have existed for some time in commercial or special-purpose codes. The large-scale, integrated capabilities necessary for this type of undersea imaging research were not available in either research or commercial form.

Only in the last few years has the requisite level of modeling capability been brought to bear on the transducer problem. We did this in the context of medical imaging by developing the code, PZFlex, for time-domain solution of the electromechanical equations governing piezoelectricity, structural dynamics, and wave propagation. The foundation wave propagation, time-domain code, Flex, has been used extensively for DoD weapons effects applications by us over the last decade. Flex was augmented and applied to medical ultrasound applications under NSF SBIR grants (Phase I and Phase II) [1].

The modeling code is described in [1] and [3]. A review is given in the Appendix, from a presentation made to the TTCP Committee on June 11, 1993 at Strathclyde University, Glasgow, Scotland.

INTRODUCTION

Under this project we applied ultrasound computer modeling technology to the high-resolution undersea imaging problem. This amounts to transferring the medical ultrasound modeling code back to DoD applications, which is both technologically efficient and cost-effective. The focus for this transfer is a collaborative (TTCP) effort on transducer design originally centered on Professor Gordon Hayward and his group at the University of Strathclyde, Glasgow, Scotland.

At the 1993 TTCP feasibility workshop at Strathclyde we confirmed that Prof. Hayward's group was in an ideal position to use this modeling code effectively. They had a range of ultrasonic applications including projects in composite transducers, imaging, and NDE, and over the previous five years did extensive finite element analyses using ANSYS. However, more recently they became frustrated by the ANSYS code's practical limits for transducer analysis and were therefore receptive to new, more comprehensive modeling technology. Potentially they were the best and most capable academic group we could work with in the context of high-resolution imaging, experimentation, and numerical simulation.

During this project Weidlinger Associates provided its electromechanical, time-domain, finite element code, PZFlex, to Prof. Hayward's group at Strathclyde and supported their use of it during a two year collaboration. On the part of Weidlinger Associates this involved code installation on their workstations, tutorials, continuous operational support, and selected areas of programming support. On the basis of their experience, interests, and hardware they were able to make a productive transition to PZFlex finite element modeling.

This project involved two categories of support for Strathclyde, *operational* and *programming*. The level of *operational* support was dictated by their problem solving/analytical expertise, numerical modeling experience, and computer prowess. The level of *programming* support, i.e., code modifications or enhancements, depended on physical modeling requirements and how well the code, as delivered, met them.

Operational support requirements were moderate because, although Prof. Hayward's group consists of bright, motivated researchers, they were, nonetheless, graduate students with disparate motivations, responsibilities, and schedules. Despite experience with ANSYS they had little exposure to time-domain modeling issues, explicit algorithms, etc. Therefore, we helped with technical orientation, modeling, interpretation, and host hardware details, including model setups and trials, preliminary computer runs at our office, and extensive discussions throughout their efforts. The point was to bring them up to speed quickly and correctly. This required about two months/year of support time, i.e., six hours per week. Training for Dr. Jeremy Bennett, then a graduate student, was done in October 1994.

Discussions with Prof. Hayward indicated a variety of transducer modeling problems that needed *programming* support. These included: 1D and 2D array designs for operation in gases, liquids, and solids; stacked (multi-layer) transducers with varying geometrical and vibration characteristics; and multi-element, multi-electroded configurations for so-called smart transducers. This problem variety required a number of enhancements to the existing code including element-by-element poling (for nonuniform electric fields), axisymmetric elements (for cylindrical single-element transducers), and skewed piezoelectric elements (for highly curved or nonorthogonal piezoelectric surfaces). About two months/year were dedicated to such modifications. An additional code enhancement was done for far-field extrapolation of transient pressure fields in an acoustic medium. This allowed the user to analytically continue the pressure wave form through a homogeneous acoustic medium from the near-field pressure calculated within the finite element model. The only alternative was to directly extend the finite element model through the medium, but this approach is limited by computer memory.

TECHNICAL ACCOMPLISHMENTS

A technical paper [2] describing the composite transducer modeling capability was presented at the 1994 IEEE Ultrasonics Symposium and published in the Proceedings. It is included as part of this final report. In addition, a chronological summary of overall project progress is provided by title pages and abstracts from the TTCP meetings and ONR reviews from 1994 through 1996. The TTCP meetings were held at the Naval Research Laboratory, Orlando, FL (1994, 1995), the Defense Research Agency, Holton Heath, U.K. (1994), Strathclyde University (Ross Priory), Glasgow, Scotland (1995), and the Coastal Systems Station, Panama City, FL (1996). The ONR Review meetings were held at The Pennsylvania State University, State College, PA (1994, 1995, 1996). The paper and titles/abstracts constitute the remainder of this report. Other modeling papers relevant to the project are [3, 4].

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TIME-DOMAIN MODELING OF COMPOSITE ARRAYS FOR UNDERWATER IMAGING

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ABSTRACT

Time-domain, finite element simulations are used to explore some design issues and the practical modeling envelope for 1-3 composite arrays in underwater pulse-echo imaging transducers. This provides a relatively new perspective on the design problem via large-scale 2D and 3D transient simulations that include many piezoelectric pillars within the composite. Cross-talk from a prototype 150 kHz array is modeled and compared to data. Some of the composite slab's dispersion behavior is derived from its impulse response and used to interpret cross-talk. Numerical experiments on a 500 kHz design demonstrate effects of pillar taper and distribution—freedoms offered by injection molding. Fourier optics manipulation of the projected acoustic field is illustrated. These studies support an ongoing design and fabrication collaboration under the aegis of United States and Commonwealth naval agencies. Our role is to provide multi-dimensional, global modeling methods that complement semi-analytical approaches, as part of an effort to increase performance of broadband imaging sonars in the 100 kHz to 1 MHz range.

INTRODUCTION

Composite transducers are *engineered piezoelectric multi-phase materials* tailored to design tradeoffs in acoustic array applications [1,2]. Our interest is in modeling composites with 1-3 connectivity, namely, 1D-connected piezoceramic (pillars or rods) in 3D-connected polymer (matrix). A typical layout is illustrated in Fig. 1 from a 150 kHz prototype. This $\lambda/2$ thickness-resonant block is sandwiched between a backing material and impedance matching layer(s) for pulse-echo imaging applications. 1-3 composites are conventionally manufactured by the dice-and-fill technique, which is rather labor intensive but nonetheless quite effective. An injection molding method for the piezoceramic [3] has recently been developed to the point that it offers significant advantages, certainly in cost for high volume applications, and likely in performance as well. A good overview of fabrication technologies and tradeoffs is given in [4].

The principal electromechanical advantages of 1-3 piezoceramic composites, over single phase transducer materials, are higher coupling in the thickness mode, lower mechanical impedance, reduced lateral mode interference, and better electrical load matching. Low lateral cross-talk and broadband behavior are achievable by choices of composite phases and layout, e.g., piezoceramic volume fraction, pillar shape, alignment and spacing, electrode coverage, as well as matching layer(s) and backing. Unfortunately, design tradeoffs are generally exclusive, e.g., bandwidth versus transmitted power.

Composite designs are usually based on 1D [5], equivalent medium [6], and Bragg scattering [7,8] analyses. They are further refined via prototype experiments. In many cases this is sufficient, but poorly quantified 2D and 3D wave phenomena can still degrade performance. To better understand and accommodate these multi-dimensional effects, researchers and designers are trying to rely on numerical modeling, e.g., [9]. For various reasons this has been restricted to implicit, frequency-domain analysis in relatively small-scale models, e.g., a few composite cells with lateral periodicity in geometry and excitation. However, by applying a time-domain finite element algorithm to the electromechanical equations we are able to increase the scale and scope of feasible simulations substantially [10].

Time-domain, finite element modeling is a design and experimentation tool. It complements traditional theory and experiment by combining them in a computer setting with the potential for much *higher resolution* of electromechanical phenomena. In principal it is only limited by knowledge of the model's geometry, material properties, and boundary (interface) conditions. In practice, of course, modeling is also limited by computer resources. These are less of an issue now, with the ascendance of UNIX workstations, powerful PCs, and inexpensive memory. The need for complete model characterization is the principal modeling limitation today. However, this should not be looked upon as a bane. Even in the context of traditional methods it is incumbent upon designers to know their materials, otherwise faulty interpretations are inescapable.

The modeling applied here to 1-3 composites is intended to support a design and fabrication effort that includes United States and Commonwealth naval agencies, contractors, and universities. One of the principal objectives is to build and demonstrate broadband, high

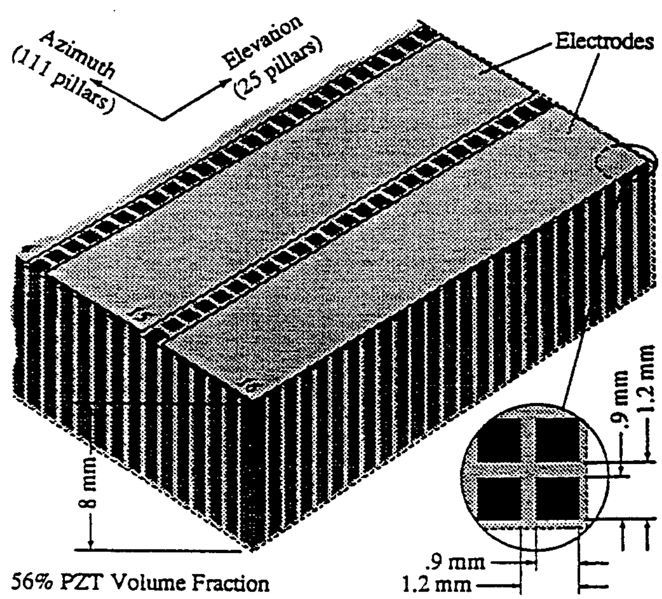

Figure 1. Drawing of pillar and electrode details in a 150 kHz 1-3 composite block. This is a prototype for an electronically scanned imaging sonar made by UDI-Wimpol, Ltd.

resolution imaging arrays for target characterization using injection molded 1-3 composites built by Material Systems, Inc. [3]. What follows is a preliminary exploration of modeling requirements and techniques for an evolving collaboration between ourselves, Prof. Gordon Hayward's Ultrasonics Research Group at the University of Strathclyde, Glasgow, Scotland, and Charles Desilets at Ultrasound Solutions, Inc.

TIME-DOMAIN MODELING

Under a National Science Foundation SBIR grant [11] we recently added piezoelectric and acoustic capabilities to our production finite element wave propagation code. This core code has been used by us and others over the last 13 years for large-scale, 2D/3D modeling in applications ranging from seismology and geophysics to nonlinear shock and vibration of structures to integrated optics and IC microlithography. The difference between our approach to transducer analysis and virtually every other discrete method reported is that we solve the spatially discretized electromechanical equations in the time-domain using a mixed explicit/implicit algorithm. The prevailing implicit finite element algorithm for transducer problems was first described in [12] and similar approaches have been applied regularly since, e.g., [13-18], with ANSYS [19] filling the commercial niche lately.

Explicit time integration is well known and arguably the most natural method for calculating broadband, wave-type phenomena. It is used primarily in the context of finite difference spatial discretizations (rather than finite element) and the underlying theory was well documented over 66 years ago [20]. In fact, it provided the basis for some of the first numerical solutions of partial differential equations on a digital computer [21]. Our explicit time-domain code, PZFlex, which incorporates facets of both finite difference and finite element discretizations, is described in [10] with validations and illustrative applications. During the last 18 months it has been used within the U.S. medical ultrasound industry and achieved wide acceptance.

PZFlex combines explicit solution of the dynamic elastic and acoustic fields with implicit solution of the quasi-static electric field, i.e., it applies an optimal solver to each electromechanical equation. The implicit electric field calculation is done directly (Gaussian elimination) or iteratively (preconditioned conjugate gradient), depending on problem size and dimension. Both the explicit integrator and the iterative solver operate on an element by element basis. The important consequence is that computer resource requirements grow linearly with the number of elements, rather than as some power, which is the case for fully implicit, direct methods. Thus, our approach eliminates manipulation of large, sparse, symmetric systems of equations. It can therefore solve much larger problems, generally 100x-1000x, or execute the same size problem much faster, typically >100x, and is more amenable to vectorization and parallelization.

Models are composed of rectangles in 2D and bricks in 3D. These finite elements may be skewed but we make every effort to keep them Cartesian, permitting much faster model definition and problem execution. Only in the exceptional situation is accuracy degradation a problem, in which case the grid is typically refined. Integration time step is chosen automatically by the code to be less than the shortest transit time of the fastest electromechanical wave between adjacent nodes in the model. Models are necessarily truncated in space, where a high-efficiency radiation boundary is applied (in any medium) to suppress nonphysical reflections. The model's electromechanical properties are fully anisotropic and material-dependent damping may be mass-proportional, stiffness-proportional, Rayleigh, viscoelastic, and viscous, each exhibiting a characteristic frequency dependence. Specification of arbitrary frequency dependence in the time-domain remains a topic of research, e.g., [22]. Circuitry in the form of RLC networks and transmission lines is incorporated directly in the time-domain solution algorithm. Pre- and post-processing, including PostScript graphics and on-screen movies, are an integral part of the code.

COMPOSITE ARRAYS

As a practical basis for modeling we use a 1-3 composite built by UDI-Wimpol, Ltd., Aberdeen, Scotland, for a pulse-echo imaging transducer in an electronically scanned 150 kHz prototype sonar system. The composite block is made of 0.9 x 0.9 x 9.4 mm PZT-5H pillars (Vernitron, see [7] for properties) separated by a 0.3 mm wide kerf filled with polymer (Araldite, V_L=2150 m/s, ρ=1120 kg/m^3). This gives a 1.2 mm pillar pitch and 56% PZT volume fraction. The complete block is 25 pillars (≈30 mm) in elevation and 111 pillars (≈133 mm) in azimuth. The top and bottom surfaces are electroded with every seventh row (in elevation) clear, defining a 16 element array with 8.5 mm electrode pitch and six pillar rows under each. Overall layout of the block is shown in Figure 1. The prototype transducer uses an 8.0 mm block between a 4.5 mm matching layer (Stycast, V_L=2800 m/s, ρ=1100 kg/m^3) and a backing block of filled polyurethane (V_L=2400 m/s, ρ=600 kg/m^3). Although various measurements have been made on the block and transducer, incomplete knowledge of wavespeeds, damping, and electroding discourages us from trying any but the simplest comparison pending further measurements.

In addition to the 150 kHz prototype we consider numerical experiments on a 500 kHz high resolution imaging transducer design. PZT-5H pillars are 3.27 mm x .6 mm and the filler is epoxy (Ciba-Geigy CY1301/HY1300, V_L≈2700 m/s, V_S≈1443 m/s, ρ=1148 kg/m^3). The matching layer is 1.23 mm thick (silicone rubber, V_L≈1820 m/s, V_S≈549 m/s, ρ=1050 kg/m^3) and the backing is tungsten-filled epoxy (Ciba-Geigy CY208/HY956, V_L≈716 m/s, V_S≈344 m/s, ρ=6932 kg/m^3). Layout, illustrated in Fig. 2, and materials were suggested in part by Desilets [23], and Hayward and Bennett [24]. At least three pillars are included across the electrode to increase electromechanical coupling [9]. At 500 kHz the wave length in water is λ_0 = 3 mm and the block's elevation dimension, d_e=6.6 mm, is chosen for a far-field (continuous wave) beam spread of $\angle_e$=27°=2sin$^{-1}(\lambda_0/2d_e)$. Its azimuthal dimension, d_a=196 mm (8 joined 24 mm blocks, 64 electrodes total) is chosen so that beam spread $\angle_a \leq 1° \approx \lambda_0/d_a$. We anticipate that this device will be manufactured by injection molding, which gives more latitude in pillar shape and distribution than the dice-and-fill approach. Consequently, this model is used to examine a few effects of pillar taper and distribution.

CROSS-TALK COMPARISON

Mechanical cross-talk is an intrinsic property of 1-3 composites given their 3D elastic connectivity. Cross-talk modeling is investigated by comparison to measurements on the 9.4 mm UDI block in air. This

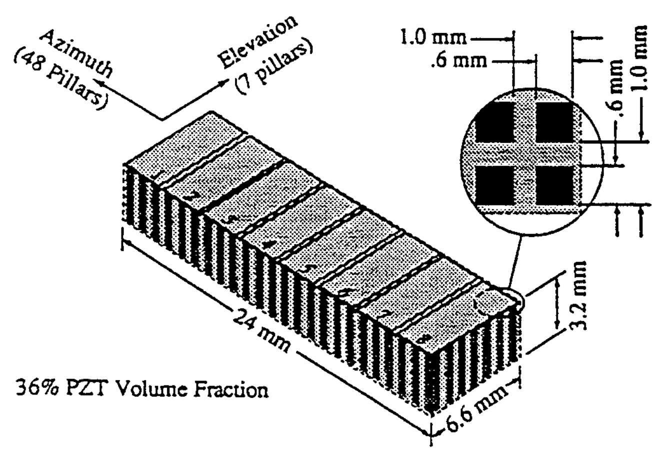

Figure 2. Drawing of pillar and electrode layout in a 500 kHz 1-3 composite design for high resolution imaging, to be made by injection molding. Eight blocks might be bonded end-to end to complete the array.

comparison minimizes model uncertainty since only PZT and one polymer are involved. Poisson ratio of 0.4 is assumed for the soft-set polymer and the shear modulus quality factor is assumed to be $Q_{shear} \approx 25$ at 150 kHz. Mechanical loadings by electrodes and air are ignored. The 3D finite element model includes two neighboring electrodes on each side terminated by an absorbing boundary condition (with the last pitch replaced by average properties). All symmetries are used to reduce model size, namely, reflection in azimuth and thickness, and periodicity in elevation. The model is 25x300x8 = 60,000 elements and runs in 5.2 hours on an HP 715/75 workstation.

The measurement was made by driving an electrode near the center with a 3.6 μs, 10 V square wave and recording voltage at adjacent electrodes. Plots of data versus calculated cross-talk on the two neighboring electrodes are presented in Figure 3. The data show an initial pulse followed by a lower amplitude coda. Signal delays in the data give 1500 m/s for the initial pulse wavespeed. At the first electrode the calculation leads the first pulse slightly but agreement is generally good, while the coda is too high and out of phase. At the second electrode the calculation leads the first pulse significantly but still follows its form, while the calculated coda is much higher, about the same amplitude as at the closer electrode.

Electrical cross-talk to the adjacent electrode is apparent in the data during the 3.6 μs excitation but not in the simulation. Increasing dielectric constant in the polymer by a factor of 8 over the manufacturer's specified value (5 ε_0) yields a fit but this discrepancy is unreasonable. The 3D, time-dependent electric field calculation has been verified so we cannot explain the lack of electrical cross-talk from the model. In general, these results indicate that the code is able to simulate mechanical cross-talk in the composite block on a practical 3D scale.

DISPERSION ANALYSIS

Electromechanical waves propagating laterally in the composite are dispersed by its finite thickness and periodic structure. In other words, the characteristic lengths cause phase velocity to depend on frequency. Current theory [7,8] provides a qualitative understanding and guidelines for design, but is limited by the failure of classical analysis in realistic composites. In this regard numerical modeling is no panacea but it does permit some useful quantification of dispersion behavior in

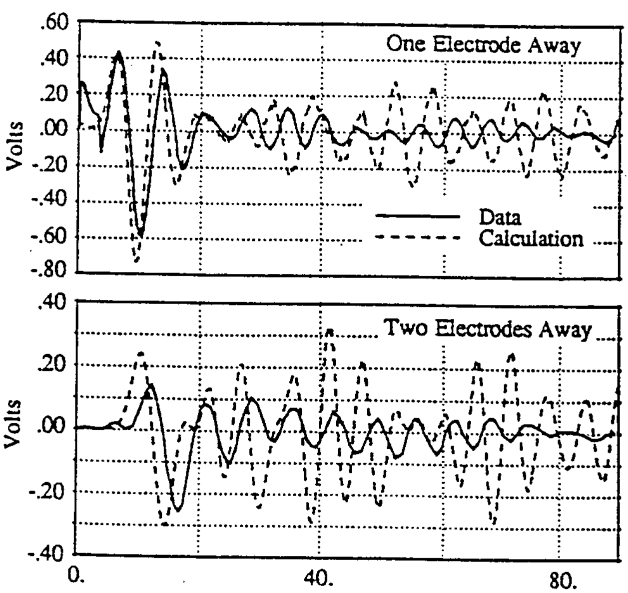

Figure 3. Comparison of measured and calculated cross-talk in the 9.4 mm UDI composite block at two electrodes next to the driven electrode.

composite blocks.

To quantify dispersion, in azimuth say, the model must extend over many electrodes to allow sufficient time and distance for separation of the wave phases. The computer memory required makes 3D models of the UDI block impractical. Therefore, a 2D cross-section through pillar centers is substituted—effectively representing the 1-3 by a 2-2 composite "plate," which ignores periodicity in elevation. Despite this approximation the predicted dispersion behavior should be close by virtue of incorporating the important characteristic lengths (block thickness and width and pitch of pillars and electrodes). Fidelity of the 2D model may be increased by using averaged properties in elevation while retaining detailed properties in azimuth, although this is not done here.

The method consists of impulsively driving the center electrode of the long 2-2 model and plotting normal velocity versus time at the top (center) of each pillar. This is a common means of presenting and analyzing seismic phases in geophysics, i.e., to identify body waves and surface waves or waveguide modes. The result is a plot of arrival time (vertical) versus distance (horizontal), shown in Fig. 4 for the block in air, where velocity (modified log) is plotted in gray-scale. Moving vertically above any pillar location shows the velocity time-history there and moving horizontally at any time shows the surface waveform along the model. Examples are plotted above the figure. By drawing a line through coherent arrivals we can identify discrete wave phases or groups. Slope of the line gives the wave slowness (inverse velocity, c), while vertical and horizontal spacing between peaks gives predominant period (inverse frequency, f) and wavelength, λ, related by $f=c/\lambda$.

Three coherent arrival loci are identified in Fig. 4 as S1, S2, and S3, ordered by increasing slowness (slope). S1 is the first arrival at any station, with a velocity (inverse slowness) of ≈1800 m/s, a predominant frequency of ≈120 kHz, and a wavelength of ≈15 mm. Since 1800 m/s is the average shear wave speed calculated in a 1D composite array model, S1 is a horizontally propagating shear (SV) wave in the 2D composite plate. No earlier phase is evident at higher magnification, hence, longitudinal precursors are virtually nonexistent. S2 yields a velocity of ≈1100 m/s, predominant frequency of ≈177 kHz, and wavelength of ≈6.2 mm. This is typically the highest amplitude signal in any record away from the driven electrode. S3 is the locus of S2 arrivals and indicates a velocity of ≈476 m/s. S2 and S3 correspond to a composite plate mode (Lamb-type wave) with phase velocity S2 and group velocity S3, i.e., signal and energy propagation speeds, respectively.

Figure 5 shows the same analysis for the in-situ block—in water, sandwiched between matching and backing. Phase S0 appears as a precursor to S1 with velocity ≈2900 m/s, frequency ≈185 kHz, and wavelength ≈25.3 mm; it is the longitudinal wave through the matching layer. S2, the "SV" wave in the plate is slower now, ≈1600 m/s, ≈154 kHz, and ≈10.4 mm. Phase and group velocity of the plate wave, S2 and S3, are ≈1230 m/s and ≈540 m/s at a predominant frequency of ≈220 kHz and ≈5.6 mm wavelength. S2 velocity is close to the shear wave speed in the backing (1150 m/s). Another plate mode appears with phase velocity S4 ≈1320 m/s and group velocity S5 ≈320 m/s, at ≈220 kHz frequency and ≈ 6.0 mm wavelength. An interesting observation is the left propagating group reflecting off the left end at ≈200 μs and continuing to the right as a coherent group to the top of the plot. This is Bragg scattering from the periodic pillars. It produces the low amplitude, long period oscillation seen in the velocity time-histories at the top of Figure 5.

ACOUSTIC FIELD EXTRAPOLATION

A comprehensive modeling capability must evaluate and manipulate acoustic fields over the homogeneous region in front of the transducer. However, computer memory limits the coverage, severely so in 3D. In addition, dispersion caused by propagating many wave lengths (i.e.,

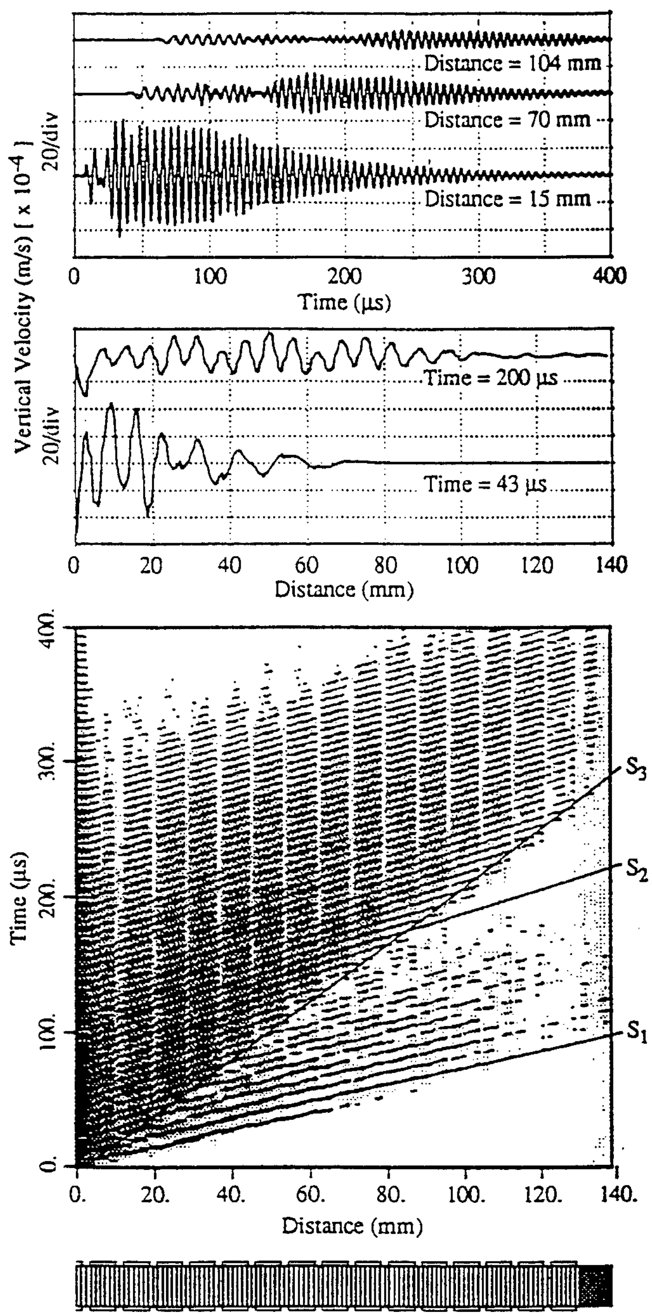

Figure 4. Dispersion analysis of the block in air from plot of normal velocity on the block surface versus time for each pillar position.

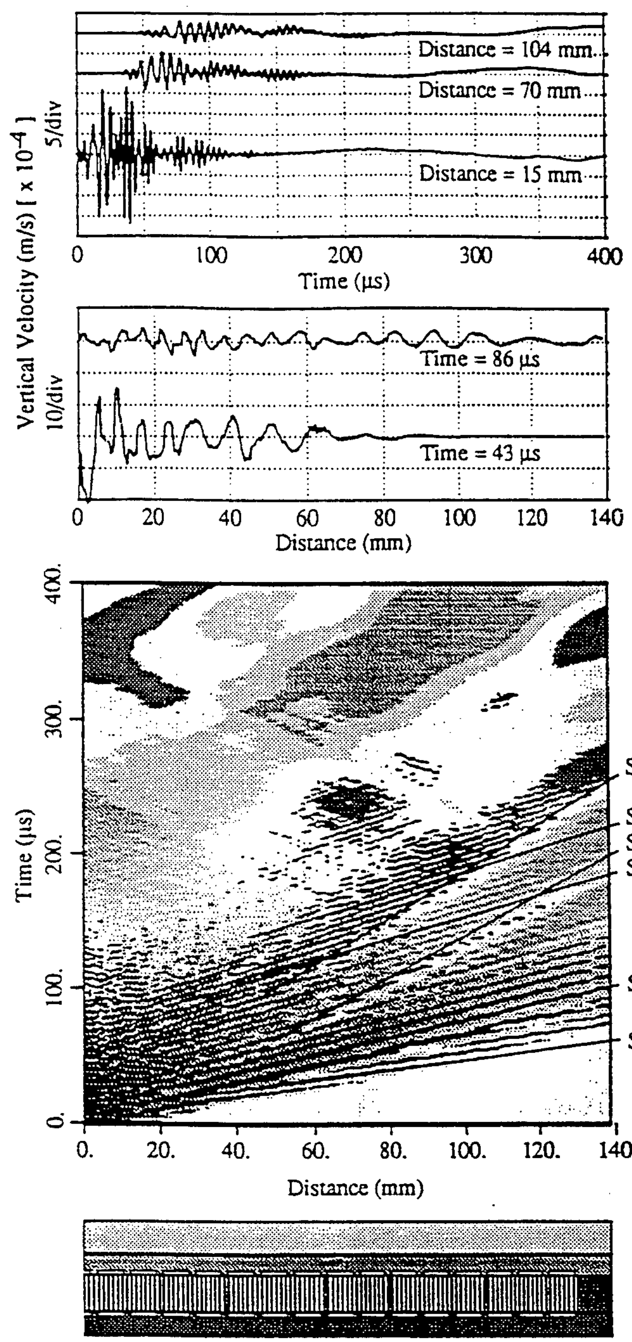

Figure 5. Dispersion analysis of the transducer in water from plot of normal velocity on the block surface versus time for each pillar position.

hundreds) through a numerical grid distorts pulses unless the algorithm is specially optimized, at the expense of structural model performance. The recourse is, of course, to use some semi-analytical field extrapolation scheme in the water. The classical approach is the Kirchhoff integral on a surface surrounding all sources in the homogeneous, scalar (acoustic) medium. This involves integration of the source distribution and Greens function over a surface and over time for each output point. We have incorporated a time-domain Kirchhoff extrapolation algorithm in PZFlex, which will be described elsewhere.

Here we consider an attractive alternative, Fourier optics [25], which is simply a linear systems reformulation of Kirchhoff diffraction theory. In the case of projected fields it consists of a sequence of time- and space-Fourier transforms on pressure-time records over a plane (line) in front of the transducer, called the *object* plane. First, records are time-Fourier transformed into frequency spectra. Second, at each frequency the spatial distribution is space-Fourier transformed into angular spectra. This is the critical decomposition into evanescent and propagating plane waves at each frequency. Third, amplitude and phase of the plane waves are modified to account for propagation to the *image* plane through free space, apertures, and/or lenses. Fourth, the modified angular spectrum at each temporal frequency is inverse transformed giving temporal spectra on the image plane. And fifth, the temporal spectra are inverse transformed, yielding pressure-time records on the entire image plane. In practice this sequence of Fourier transforms is performed by the FFT algorithm on uniformly sampled space-time data.

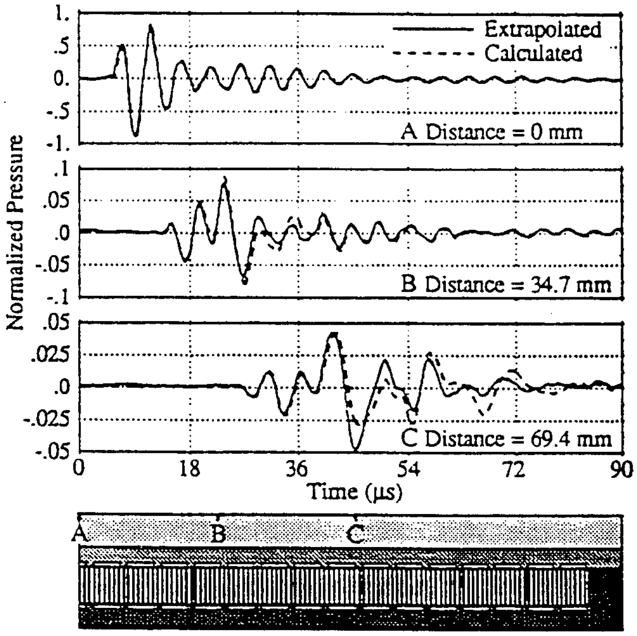

Figure 6. Validation of Fourier extrapolation of pressure on the wet side of the matching layer to points near the boundary of a shallow water layer.

In a sister code, EMFlex, we use Fourier optics to image light transmitted and diffracted by photomasks in submicron IC lithography [26]. A subset of these routines is applied to the transducer problem. Our validation example consists of the UDI transducer model with 8 mm of water beyond the matching layer, drawn in Figure 6. The left electrode is driven impulsively. Pressure just outside the matching layer over the model is extrapolated to a plane 2 mm below the top of the finite element acoustic domain. Extrapolated and finite element calculated pressures are compared there at three points. This is a typical example of how extrapolation is used, i.e., making the water very shallow in order to save elements for structural parts of the model. In this case the radiation boundary conditions are actively removing waves (and reflecting some unavoidable noise) for 88 µs during the extrapolation. The error observed in the extrapolation is the same magnitude at the three points and is caused by truncation of the pressure on the object plane (on the right), truncation of the signals in time, as well as noise in the grid.

NUMERICAL EXPERIMENTS

Besides its use in design, discrete numerical modeling is a useful experimental tool. For example, the designer can postulate interesting composite block or transducer configurations, test them on the computer (within the limits of memory and speed), and quickly focus design and experimental efforts on the most promising approaches. Preliminary numerical experiments are done here to look at effects of pillar shape and distribution. This is motivated by the geometrical freedom offered by injection molding, in contrast to the dice-and-fill method.

The effect of pillar distribution on cross-talk is examined for the 500 kHz preliminary design sketched in Fig. 2 Every other pillar row, in azimuth say, of the 500 kHz layout is staggered 1/2 pitch (0.5 mm) and cross-talk to the first and second neighbor of the driven electrode is compared to that in the regular (Cartesian) distribution. The 3D model is 1/2 pitch in elevation for the regular spacing and 1 pitch for the staggered. It includes 1/2 of the driven electrode and two neighbors on one side. Cross-talk voltage is Fourier transformed and the spectra are normalized by the driving spectrum. Results are shown in Figure 7.

We also consider effects of pillar taper on radiated sound. Initial models are 2D since all behaviors should be exhibited qualitatively. Three shapes are modeled, each with the same volume fraction, namely,

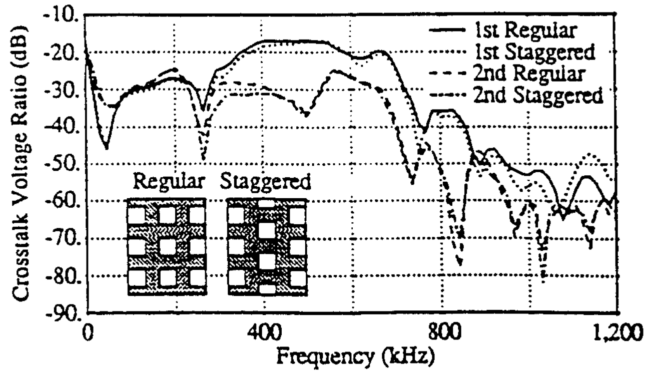

Figure 7. Cross-talk to the 1st and 2nd electrodes versus frequency for regular and staggered pillars in the 500 kHz composite design.

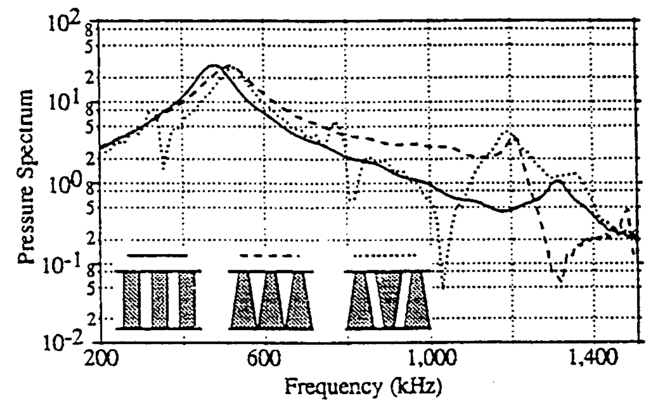

Figure 8. Pressure spectrum 4.5 mm in front of the three taper cases.

straight pillars, pillars tapered in one direction, and pillars tapered in both directions. Shapes are shown in Figure 8. The bare plate is fully electroded and driven impulsively in water, without matching layer or backing. The pressure is measured 4.5 mm above the plate for each taper case, Fourier transformed, and cross-plotted in Figure 8.

SUMMARY AND CONCLUSIONS

Time-domain finite element modeling is applied to 1-3 composites for underwater imaging arrays. The code used, PZFlex, often permits two orders of magnitude larger models or faster solutions than the implicit codes reported in the literature for transducer analyses. It is currently used by a number of commercial ultrasound companies. The composites modeled include a 150 kHz block built by UDI-Wimpol, Ltd. for a prototype electronically scanned imaging sonar and a preliminary 500 kHz design for an ONR program. These studies set baselines for an active design collaboration with the Ultrasonics Research Group at the University of Strathclyde.

In preparation for code validation against more complete UDI experiments, we model measured voltage cross-talk for the block in air. Models are severely limited by incomplete material properties. Nonetheless, correlation is reasonable in this case and serves as a qualified validation of the model until more complete material data are available. Note that from the dispersion analysis it is clear that arrival time errors in calculated cross-talk are caused by too high a shear velocity assumed in the polymer fill (1800 m/s versus 1500 m/s). This implies that the polymer's Poisson ratio should be increased from .4 to .45.

A 2D model is used to investigate dispersion behavior of the UDI composite—both the bare block in air and the potted block with matching layer and backing in water. This is done by plotting vertical velocity across the block's surface for an impulsive voltage applied at one electrode. Pictures delineate the various plate waves nicely, including

coherent Bragg reflections and associated long period waves. Mode shapes and velocity polarization can also be examined for classifying phases.

Time-domain dispersion analysis is useful because it identifies the various signals and suggests ways of reducing cross-talk in multi-electroded designs. For the composite in air, the first signal is from the horizontally propagating shear type wave (S1) and subsequent lower amplitude ringing is from the plate wave group (S2). However, in air the plate wave group amplitude is higher than the shear wave, so why is its resulting cross-talk lower? This depends on the number of wavelengths under the electrode (width L). A simple calculation shows that cross-talk is proportional to $\lambda\sqrt{1-\cos(2\pi L/\lambda)}$. Therefore, signal is reduced in part because S2's wave length is about half of S1's. Furthermore, there is signal extinction for an integer number of wave lengths under the electrode ($L/\lambda = N$). If the Lamb-type wave length nearly satisfies this condition then additional cancellation will occur. Mode shape of each phase may also contribute to differences in cross-talk.

We demonstrate a Fourier optics (acoustics) algorithm that analytically models sound propagation in water beyond the finite element grid. It transforms fields evaluated on an object plane to an image plane of the same size at any distance. The method is validated against a finite element calculation of the UDI 2D model in water and works as predicted. By imaging with and without evanescent wave truncation we find that evanescent waves are negligible beyond $\lambda_0/2$ from the matching layer. Fourier processing is fast compared to the time-domain Kirchhoff integral method but the amount of data can be prohibitive. Spectral truncation in angle and frequency should reduce memory requirements without degrading image quality. This Fourier approach will accommodate apertures, acoustic lenses, and simple reflectors in the analytical model.

Numerical experiments on pillar distribution and taper are done on a 2D, periodic model of the 500 kHz composite (uniformly electroded). The pillar distribution experiment did not indicate any dramatic effect near the design frequency. Projected pressure for the straight pillar and two forms of tapered pillar, all with the same PZT volume fraction, are compared. Taper tends to complicate the modal picture by lowering overtone frequency and increasing overtone amplitude. Uniform taper in one direction produces higher peak pressures on the narrow side of the composite plate.

These examples show that 1-3 composite transducer design issues can be addressed effectively with explicit time-domain finite element simulations. Most of the examples would have been impractical using implicit codes, either because of limited problem size or excessive run time. Despite our success here, *global* 3D models will remain impractical on workstations and PCs for the foreseeable future, but massively parallel supercomputers are a viable option. In the meantime, we expect that 2D simulations with averaged properties in the third dimension will be an effective intermediate solution in many transducer layouts.

ACKNOWLEDGMENTS

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Finite Element Modeling in Support of the TTCP Collaboration on Underwater Imaging

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Workshop on Composite Piezoelectric Materials For Undersea Ultrasonic Imaging Transducers

Naval Research Laboratory
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Finite Element Modeling in Support of the TTCP Collaboration on Undersea Imaging

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High-resolution undersea imaging for mine detection and identification is a critical capability for future naval operations. However, conventional (clear water) sonar technology does not offer a direct basis for imaging because of the seafloor environment and high-resolution needs. Therefore, transducer designs, materials, waveforms, and signal processing must be reexamined, with strong emphasis on composite, broadband transducer technology.

A useful tool in this reexamination is numerical transducer modeling. It augments physical experiments with robust computer code simulations to help the designer interpret experimental data, quantify phenomena, validate solutions, and reduce design-cycle time. Traditional codes have been around for years but the large-scale, integrated capability necessary for this TTCP research appeared only recently, when we brought it to bear on the related medical imaging problem. Our workstation-based code incorporates a finite element algorithm for time-domain solution of the electromechanical equations governing piezoelectricity, structural dynamics, and wave propagation. It is well suited to the characteristic dimensions and wavelengths of transducers envisioned for undersea imaging.

Key elements of the modeling capability are speed and accuracy. Speed is obtained from a mixed explicit/implicit algorithm for the electromechanical equations, rather than the traditional implicit algorithm. We demonstrate performance gains greater than 100 in speed and size. Accuracy is enhanced by very efficient radiation conditions over the elastic and acoustic truncation boundaries of the model. Many of the discrepancies observed between well-characterized experiments and calculations are caused by poor radiation conditions.

It should be emphasized that without properly characterized materials and geometries, computer modeling loses much of its value. Clearly, material characterization is of critical importance. We describe a method that utilizes modeling in an ad hoc "inversion" scheme to help quantify material properties based on comparisons to relatively simple experiments. The method depends critically on a fast, accurate simulation code to perform many parameter variations on the experimental model. The potential of such an approach will be discussed.

Overall, our talk reviews the salient features of frequency and time-domain modeling, critiques algorithms, and illustrates many of the modeling issues with 2D and 3D simulation results. We try to be objective in presenting pros and cons of computer modeling in general, and frequency vs. time-domain algorithms in particular. The bottom line is that complementary use of all available research and design modalities is most effective, i.e., a mix of analysis, experimentation, and various models. Providing comprehensive modeling capabilities to the TTCP effort should help promote technical specialization and a more efficient collaboration.

Transient Transducer Response and Parameter Studies Using Explicit Finite Element Modeling

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State College, Pennsylvania

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TRANSIENT TRANSDUCER RESPONSE AND PARAMETER STUDIES USING EXPLICIT FINITE ELEMENT MODELING

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Rigorous computer modeling of transducers shows promise as a design tool. The idea is to augment physical experiments and approximate (1D) analyses with robust numerical experiments. Such models have the potential to help develop/validate transducer solutions and reduce design-cycle time. Conventional codes have been available for years but larger-scale, more accurate capabilities are necessary for comprehensive, desk-top modeling.

The talk reviews PZFlex, a workstation-based, finite element code that solves the complete 2D or 3D electromechanical equations in the time-domain. Key issues are run time, model scale, and solution accuracy. Performance gains greater than 100 in speed and size are demonstrated over conventional codes for transient problems. Accuracy is enhanced by very efficient radiation conditions on the model's elastic and acoustic truncation boundaries.

We consider models of composite transducers for underwater imaging. These are preliminary experiments under an ONR-sponsored collaboration with Gordon Hayward at the University of Strathclyde. The composite consists of PZT-5H circular cylinders in a resin matrix with matching layer(s) and backing material. We also consider a Moonie—which exhibits relatively low frequency, flexure-dominated response—to contrast transducer modeling issues. Videos of transducer response will be shown.

It should be emphasized that computer modeling loses much of its value without accurate material properties. Hence, characterization of piezoelectric and elastic/acoustic materials is of critical importance. We describe a method that utilizes modeling in an inversion scheme to help quantify material properties based on comparisons to relatively simple experiments. The method depends critically on a fast, accurate simulation code to perform many parameter variations on the experimental model.

FINITE ELEMENT MODELING OF TRANSDUCERS FOR UNDERSEA ULTRASONIC IMAGING†

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7, 8 September 1994

Finite Element Modeling of Transducers for Undersea Ultrasonic Imaging

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The objective of this work is to collaborate on finite element modeling techniques with Prof. Gordon Hayward's Ultrasonics Research Group at the University of Strathclyde. Specifically, we will provide the Ultrasonics Research Group with our time-domain finite element code, PZFlex, develop enhanced analysis capabilities within the code framework, and help apply the modeling code for a better understanding of transducers and transducer materials used in undersea ultrasonic imaging systems. In addition, to support the overall TTCP collaboration, we are looking at ways to accommodate disparate interests of the groups involved.

An ONR contract (N00014-94-C-0047) was recently awarded to Weidlinger Associates in support of the above objective. PZFlex has been delivered to the Ultrasonics Research Group at Strathclyde and is currently operational on a SUN Sparc 10 there. In view of difficulties encountered hiring a dedicated modeler at Strathclyde, Prof. Hayward has suggested putting Mr. Jeremy Bennett in charge of the modeling effort. We heartily support such a plan and are considering options that will expedite training and accelerate the overall modeling program.

Technical developments at Weidlinger Associates include a tentative 1-3 composite transducer cross-section design, preliminary numerical simulations, and a time-domain wave field extrapolation scheme. The design is a hybrid based on suggestions by Charlie Desilets (Ultrasound Solutions), Jeremy Bennett (Strathclyde), and Vic Murray (UDI-Fugro). The simulations are a first cut at studying 2D and 3D transient effects of design parameters as well as cross-talk mechanisms in the 1-3 composite slab. We have implemented a time-domain Kirchhoff integral for extrapolating the pressure field from the transducer face and are examining alternative FFT-based schemes. This capability will permit the direct calculation of far-field radiation patterns from single transducer elements or an array of many elements.

We look forward to discussing and perhaps establishing some specific goals for the application of this transient modeling capability to the low frequency hydrophone problem. This is in addition to our more immediate imaging system problem. Furthermore, we hope to enhance our transducer material models based on testing at the Royal Military College. The most important goal for the next 6 months is to see PZFlex used productively at Strathclyde. If recent successes at the major U.S. ultrasound companies are applicable, such modeling will prove very useful.

AN UPDATE ON COMPOSITE TRANSDUCER MODELING

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An Update on Composite Transducer Modeling

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Our mission within the TTCP collaboration is to support advanced finite element modeling of composite transducers in Prof. Gordon Hayward's Ultrasonics Research Group at the University of Strathclyde. We are also attempting to address modeling problems that have come to the fore in discussions with Charlie Desilets at Ultrasound Solutions, Vic Murray at UDI-Wimpol, and others. This talk describes relevant issues as well as current solutions to some of the problems.

Our finite element code, PZFlex, is currently operational at Strathclyde and we continue to develop some enhanced analysis capabilities. To bootstrap the modeling effort we brought Jeremy Bennett to our office in California for a week of training. Charlie Desilets took part in this activity as well. We expect that some of the Strathclyde perspective, based on years of implicit finite element modeling, will find its way into PZFlex as our collaboration intensifies. In general, we are pleased with the state of affairs.

On another front, we have looked at the cross-talk modeling problem in the context of composite arrays built by UDI-Wimpol and a preliminary design suggested by Charlie. An effective approach to dispersion analysis of the composite plate has been developed and we expect it to be pursued at Strathclyde. Our approach and a comparison to UDI-Wimpol data will be presented. Some effects of pillar shape and distribution will also be shown. An important issue is far-field extrapolation. We describe a Fourier optics implementation and hope to talk about alternatives. This will constitute our principal development area over the next few months.

During the last TTCP meeting at DRA, Vic Murray and Greg Wojcik discussed the thermal problem for high-power ultrasonic transmitters. Under an NIH grant addressing hyperthermia and focused ultrasound we have incorporated a transient thermal capability in PZFlex and will present some examples for composite-type arrays, illustrating thermal diffusion paths and effects of increased conductivity through the front of the array. This capability requires additional material characterization and we look forward to some suggestions.

It is crucial that we get a comprehensive set of PZT properties for modeling and for quantifying uncertainties. To this end we have taken advantage of the capabilities offered by Binu Mukherjee and Stewart Sherrit at RMC reported in earlier meetings. We have arranged with Motorola to supply IEEE standard resonator samples, and Binu and Stewart have agreed to analyze them. If this is successful, Motorola will probably make an independent arrangement with RMC for periodic characterization. RMC currently has most of these samples and Stewart should do measurements soon. These data will permit us to look at dispersion effects, and hopefully discount them. However, the most critical material characterization issue is the polymers, which is of utmost importance to the modeling effort.

ELECTRO–MECHANICAL–THERMAL FINITE ELEMENT MODELING METHODOLOGIES FOR TRANSDUCER ARRAYS

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ELECTRO–MECHANICAL–THERMAL FINITE ELEMENT MODELING METHODOLOGY FOR TRANSDUCER ARRAYS

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Rigorous computer modeling of transducers is achieving its promise as an engineering design tool—augmenting the usual physical experiments and approximate (1D) analyses with robust, multidimensional numerical experiments. In this regard we review PZFlex, a workstation-based, finite element code that solves the full 2D/3D electromechanical equations in the time-domain. Methodology issues include extended 1D and 2D array models, transient thermal models, and efforts toward more comprehensive material characterization. This work is supported in part under an ONR Contract for a modeling collaboration with Prof. G. Hayward, University of Strathclyde.

Cross-talk in composite arrays is of course an important design issue. Electromechanical waves propagating laterally in the composite are dispersed by its finite thickness and periodic structure, but current theory only provides a qualitative understanding. We describe pros and cons of a "large-scale" numerical dispersion model and use it to quantify cross-talk waves, including Bragg reflection. Examples include an existing composite plate built by UDI–Wimpol, Ltd., and a preliminary 500 kHz imaging transducer design.

Thermal effects can be a limiting factor in certain situations, e.g., high-power sonar transmitters and medical transducers operating in the Doppler mode. The designer needs to quantify maximum temperatures, diffusion paths, and effects of heat sinks or increased conductivity. Under an NIH grant on ultrasound therapy the necessary transient thermal capability has been added to PZFlex. We will present some examples for composite and medical arrays.

Without good material properties, modeling loses much of its value. The burden of piezoceramic characterization is typically born by manufacturers, and their modeling success is proportional to their measurement ability. We recently collaborated with Prof. Binu Mukherjee/Mr. Stewart Sherrit of the Royal Military College of Canada and Motorola to fully characterize Motorola PZT-type materials using IEEE standard resonator samples. We will conclude by discussing early results, including measurements and resonator models.

UPDATES TO PZFLEX FOR CURVED ARRAYS AND PERFORMANCE EVALUATION

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Updates to PZFlex for Curved Arrays and Performance Evaluation

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Abstract

At the last meeting we were presented with a curved array design for the 500 kHz imaging transducer. Our experience applying PZFlex has emphasized linear arrays, where Cartesian piezoceramic grids and the requisite stairstep modeling of interfaces are ideal, both physically and computationally. However, the Cartesian model is less than ideal for curved arrays. To address this deficiency we recently added skewed piezoelectric elements to the structural and acoustic element library, which already had this capability. These permit a good geometric representation of curved structures. There is a cost for the skewed partition in terms of model setup and increased computational time (x3-x5), but nonetheless, it is a practical and effective option and has been validated for spherical transducers and annular arrays.

We have been "beaten over the head" with beams and finally realized their importance to array performance evaluation. To this end, far-field beam patterns based on the Rayleigh-Sommerfeld integral of near-field pressure are included in the code for 1D and 2D arrays, but not yet axisymmetric. Directivity patterns have been validated against theory and large-scale finite element models. Jeremy and Gordon have incorporated their own version, which we may augment or supplant in the near future. A related topic is receive sensitivity. We need to discuss receiver modeling issues among the group. Also, an exercise we recently concluded with Charlie on a 2D array design for Ed Belcher will be described.

We conclude with discussion of a number of ancillary topics, ranging from material damping models, material properties in general, and modeling of the Sonopanel. For example, damping measurements made by Stewart and Binu indicate that damping decreases as frequency increases in the voided polyurethane, with relatively low damping in the 100-200 kHz range (Q≈50-60). Thus, the filler is not nearly as lossy as (I) expected. We just concluded the first phase of an "independent" exercise with RMC on Mototola's HD ceramic with encouraging results that support the utility of their "complex" characterization. Finally, we are looking at the Al-faced Sonopanel (4-21) to see if the observed "mysterious" resonance at ≈70 kHz appears in simulations. Some results may be in hand for the meeting.

NONLINEAR MODELING ISSUES FOR ULTRASOUND TRANSDUCERS

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NONLINEAR MODELING ISSUES FOR ULTRASOUND TRANSDUCERS

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A number of nonlinear phenomena can occur in ultrasound applications. These may involve the transducer itself (e.g., high piezoelectric driving voltage and electrostrictors) or wave propagation (e.g., shocking and cavitation) or both. Modeling these phenomena is tricky for by reason of algorithmic or phenomenological difficulties. For example, algorithms relying on linear superposition, e.g., a frequency domain approach, are of limited utility, and shocking phenomena produce high gradients or harmonics that are difficult to resolve numerically.

A algorithmic approach that works well in practice for a variety of nonlinear phenomena is the incrementally linear approximation applied to a time-marching scheme that integrates the space-discretized differential equations. At each time step the mechanical, thermal or electrical properties of each medium are updated based on instantaneous or cumulative effects like pressure, strain rate, temperature, etc.

In this talk examples are drawn from therapeutic ultrasound applications. The modeling is done using the time-domain finite element code, PZFlex, which is used commercially for medical ultrasound transducer design and has been described in previous review meetings. Nonlinear illustrations include focused ultrasound and shock propagation in water, localized heating due to temperature-dependent absorption in propagation media, and progressive "cavitation" and scattering caused by elevated temperatures in the media.

Although we have not applied the approach to transducers it solves the associated nonlinear phenomena equally well. Examples include voltage or strain dependence of piezoelectric properties, which are only linear for small signals. Also included are electrostrictors, which are inherently nonlinear (strain proportional to the square of the electric field).

CURRENT ISSUES IN COMPOSITE AND FLEXTENSIONAL TRANSDUCER MODELING

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Current Issues in Composite and Flextensional Transducer Modeling

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Under the TTCP collaboration we supply time-domain finite element software to Prof. Gordon Hayward's Ultrasonics Research Group at the University of Strathclyde, Glasgow, Scotland, and support their composite transducers modeling needs. To this end we have made a number of extensions to the code and are taking advantage of the new generation of PCs to substantially increase performance/price. We also see a need to address modeling problems that have come to the fore in design work by Charlie Desilets at Ultrasound Solutions using composites from Les Bowen and Material Systems. As a side issue we have done modeling of a barrel-stave transducer in collaboration with Dennis Jones, et al. at the DRA, Canada.

A new release of PZFlex will be out in early April incorporating extensions to beam patterns, round-trip calculations, damping, circuitry models, and modal extraction. The code has also been ported to Pentium PCs running Windows95 and WindowsNT. Future work on parallelization will be reviewed briefly.

As described during the last meeting, we have modeled one of the SonoPanel samples tested by Tom Howarth and described in previous meetings. Correlation was less than satisfactory. We are currently looking at samples without cover plates provided by MSI and characterized by Dave Powell at NRL, Orlando. By comparing models and experiments with and without cover plates we hope to establish a better theoretical baseline for MSI's composites, perhaps relevant at various scales.

Charlie Desilets of Ultrasound Solutions has presented a matrix of designs for the injection molded imaging transducer that will be used with the UDI imaging system. Performance requirements for this transducer are rather high, demanding fairly sophisticated solutions. Since Strathclyde is directed by DRA to support the UDI effort there is a need for us to provide some level of support for Ultrasound Solutions and MSI's injection molded technology. An example will be described.

In the course of this work we have collaborated with Dennis Jones at DREA, Canada in an exploratory effort to model their barrel-stave transducer design. This may suggest a related TTCP collaboration opportunity. Results are presented for a 2D (axisymmetric) idealization and modeling issues concerning full 3D simulations will be described.

All-in-all, the modeling is advancing well. However, concerted efforts addressing immediate design and experimental issues are called for. In addition, the need for comprehensive material property measurements is only partly satisfied. This latter is a major cause of disagreement, but other subtle causes remain to be identified.

APPENDIX

Electromechanical Modeling Using Explicit, Time-Domain Finite Elements

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Abstract

Piezoelectric transducers convert electrical signals directly to mechanical signals and vice versa. They serve as both transmitters and receivers in electronic imaging systems that use scattered mechanical waves to sense remote objects. Examples include sonar, medical imaging, and nondestructive evaluation. The technology, despite its relative maturity, has great potential for improvement and innovation.

However, as transducers continue to evolve it is apparent that conventional design methods are approaching practical limits of effectiveness. Comprehensive computer modeling is recognized as the solution. R&D groups are currently using older commercial finite element programs, e.g., ANSYS, or are writing their own codes based on "textbook" formulations. In most cases they enjoy only limited success and at significant development and simulation costs.

The difficulty is universal reliance on implicit numerical methods for frequency-domain analysis or time integration. This is in spite of the fact that today's applications involve transient (broadband) signals more often than not. Furthermore, as model size increases, particularly when material attenuation and radiation boundary conditions are invoked, the difficulty and expense of implicit calculations increases dramatically, prohibitively so for many 3D models.

The natural alternative to implicit methods is explicit time-domain methods that marry finite difference and finite element concepts. Not only does a single calculation yield complete transient response (linear or nonlinear), but the algorithm is more robust and computationally efficient. For larger 2D and most 3D transient problems, explicit analysis is often orders of magnitude faster than implicit analysis and affords much larger models—on the same workstation. Of course implicit modeling has its place, but not for fundamentally transient 3D phenomena.

This talk examines computational issues and options for piezoelectric transducer simulation. Emphasis is on FLEX, an explicit, time-domain finite element code for 2D and 3D piezoelectric device simulation. FLEX uses mixed explicit-implicit integration of the full piezoelectric–elastic–acoustic equations. Piezoelectric and acoustic elements were added to this proprietary code's structural and continuum finite element library under a recent NSF SBIR Phase I grant.

Modeling examples are drawn primarily from medical ultrasound transducer applications. Code validations are shown comparing simulated and experimental impedance plots for rectangular piezoelectric bars. Multi-element transducer modeling is illustrated with a 1D medical-type array, where the stack consists of

backing, electrodes, piezoelectric, matching layers, and lens. On-screen movies show details of wave interaction between array elements. A single 3D array "element" model for calculating end effects (diffractions) is used to explore 3D modeling issues.

FLEX's transient modeling speed is typically 100 times that of the proprietary implicit piezoelectric codes currently in use, and its model size advantage is much more dramatic. The code's efficiency, robustness, and built-in graphics provide designers with unprecedented capabilities for simulation of 2D and 3D electromechanical devices, both broadband and narrowband, on modern UNIX workstations.

By way of concluding, transducer and wave propagation modeling alternatives are discussed. Despite being very effective, the basic algorithms described and illustrated in this talk have been around for decades. A number of questions need serious consideration, e.g., do better algorithms exist, and how should modeling capabilities and philosophies evolve as transducer designs and computers mature?